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Summary

Strainrange partitioning (SRP) was originally developed on an inelastic strain basis for isothermal fatigue in the high-strain regime where the inelastic strainrange could be determined accurately. However, most power-generating equipment operates in the regime where the inelastic strains are small and difficult to determine with any degree of accuracy. This shortcoming led to the development of the total strain version of SRP (TS-SRP). Power-generating equipment seldom operates under isothermal conditions, and isothermal life prediction methods cannot be depended on to predict the lives of anisothermal cycles. To overcome this shortcoming, a method was proposed for extending TS-SRP to characterize anisothermal fatigue behavior and to predict the lives of thermomechanical fatigue (TMF) cycles using appropriate anisothermal data. The viability of this method, referred to as TMF/TS-SRP, was demonstrated using TMF data for two high-temperature aerospace alloys. In this report, data from the literature are used to examine the ability of TMF/TS-SRP to characterize the failure and flow behavior of three low-strength, high-ductility alloys widely used for ground-based power-generating equipment. The three alloys are type 304 stainless steel, 1Cr-1Mo-0.25V steel, and 2.25Cr-1Mo steel. Because of the limited nature of the data, it was possible to evaluate the characterization, but not the predictive capability of TMF/TS-SRP.

Introduction

Three major high-temperature creep-fatigue life prediction methods (ref. 1) are available today: (1) the time- and cycle-fraction used in the American Society of Mechanical Engineers (ASME) Nuclear Code case N–47, (2) the stress-based continuum damage mechanics approach of ONERA (ref. 2) in France, and (3) the strain-based method of strainrange partitioning (SRP) of NASA Lewis Research Center. Only the last two methods have received development in the past decade. The stress-based approach is currently used by the French aerospace and nuclear industries, whereas SRP is being used by several U.S. companies. Both methods were first developed for isothermal conditions and were later extended to include nonisothermal fatigue.

SRP was first developed on an inelastic strain basis (ref. 3) and gave satisfactory results in the isothermal high-strain regime where the inelastic strainrange could be determined accurately either by experiment or analysis. However, most power-generating equipment operates in the regime where the inelastic strains are small and difficult to determine with any degree of accuracy. This shortcoming led to the development of the total strain version of SRP (TS-SRP) (refs. 4 and 5). Isothermal fatigue is the exception rather than the rule for power-generating equipment, and isothermal life prediction methods cannot be depended on to accurately predict the lives of nonisothermal cycles (ref. 6). To overcome these problems, a method was proposed (ref. 7) for extending TS-SRP to characterize failure and flow behavior and to predict the lives of thermochemical fatigue[1] (TMF) cycles. This method is referred to as TMF/TS-SRP, and the viability of this extension was successfully evaluated in a subsequent paper (ref. 8) using TMF data for two high-temperature aerospace alloys.

Computer programs have been written to characterize failure and flow behavior and predict cyclic life using both TS-SRP and TMF/TS-SRP. These programs (TS-SRP/PACK, LEW-15653) were written for IBM-compatible personal computers; and a users manual (ref. 9), together with an extensive high-temperature creep-fatigue data base suitable for use with other life prediction methods, is available from the Computer Software Management and Information Center (COSMIC)[2] for public dissemination.

In this report, data from the literature have been used to examine the ability of TMF/TS-SRP to characterize the failure and flow behavior of three low-strength, high-ductility alloys

[1]The term "thermomechanical fatigue" indicates variable-temperature fatigue with the mechanical strains imposed only by external loads. Temperature gradients within the test volume are not allowed.

[2]COSMIC, 382 East Broad St., Athens, GA 30602–4272; (706) 542–3265, FAX (706) 542–4807, INTERNET:SERVICE@COSSACK.COSMIC.uga.EdU.

widely used for ground-based power-generation equipment. The three alloys are type 304 stainless steel (refs. 10 and 11), 1Cr-1Mo-0.25V steel (ref. 12), and 2.25Cr-1Mo (refs. 13 and 14). Because of the limited nature of the data, it was not possible to fully evaluate the predictive ability of TMF/TS-SRP.

Symbols

A'	general constant in empirical flow equation
B	intercept of elastic strainrange-versus-life relation
C	intercept of inelastic strainrange-versus-life relation
C'	intercept of equivalent inelastic line for combined creep-fatigue cycles
CC	creep strain in tension, creep strain in compression
CP	creep strain in tension, plastic strain in compression
F	strain fraction, $\Delta\varepsilon_{ij}/\Delta\varepsilon_{in}$
K	cyclic strain-hardening coefficient
N	number of cycles to failure
PC	plastic strain in tension, creep strain in compression
PP	plastic strain in tension, plastic strain in compression
R	ratio
V	ratio of mean to amplitude
t	hold time per cycle
y	independent variable representing several flow terms
Δ	range of variable
ε	strain
σ	stress

Subscripts:

c	compression
cc	creep strain in tension, creep strain in compression
cp	creep strain in tension, plastic strain in compression
el	elastic
eff	effective
fm	failure with mean stress present
fo	failure without mean stress present
in	inelastic
ij	PP, PC, CP, CC
max	maximum
min	minimum
pc	plastic strain in tension, creep in compression
pp	plastic strain in tension, plastic strain in compression
pre	predicted
t	total or tension
σ	stress
y	independent variable representing several flow terms

Superscripts:

b	power of cyclic life for elastic strainrange-versus-life relation
c	power of cyclic life for inelastic strainrange-versus-life relation
m	exponent on time in empirical flow equation
n	strain-hardening exponent
α	exponent on total strainrange in empirical flow equation

Cycle type (thermomechanical):

TMIP	inphase continuous cycling
TMOP	out-of-phase continuous cycling
CHOP	compressive strain hold out-of-phase (pp + pc strain)
THIP	tensile strain-hold inphase (pp + cp strain)
FSOP	fast-slow out-of-phase (pp + pc strain)
SFIP	slow-fast inphase (pp + cp strain)

Analysis

TS-SRP has been discussed in detail elsewhere (refs. 5, 7, and 15), so we restrict this discussion to a brief overview. Reference 15 is recommended to readers not fully familiar with SRP. A key assumption in simplifying TS-SRP is that the elastic and inelastic strainrange-life relations for cycles with creep are parallel to the corresponding PP elastic and inelastic lines as indicated in figure 1. This assumption results in simple equations relating failure and flow behavior. Failure behavior is expressed by equations for elastic and inelastic strainrange versus cyclic life for a theoretical zero mean stress condition.

$$\Delta\varepsilon_{el} = B\left(N_{fo}\right)^{b} \tag{1}$$

$$\Delta\varepsilon_{in} = C'\left(N_{fo}\right)^{c} \tag{2}$$

where

$$C' = \left[\sum F_{ij}\left(C_{ij}\right)^{1/c}\right]^{c} \tag{3}$$

Equation (3) is obtained from the four generic SRP failure relations and the interaction damage rule (IDR) (ref. 16), with the subscripts *ij* denoting the type of cycle (pp, pc, cp, or cc). The four generic SRP relations for a theoretical zero mean stress condition are

$$\Delta\varepsilon_{in} = C_{ij}\left(N_{ij}\right)^{c} \tag{4}$$

The IDR is expressed by the following equation:

$$\sum\left\{F_{ij}/N_{ij}\right\} = 1/N_{fo} \tag{5}$$

No more than three of the four types of strains (pp + cc + pc {or cp}) can appear in a stress-strain hysteresis loop. For TMF conditions, *cc* type strains are expected to be negligibly small if they occur at all.

Flow behavior is described by the following equation:

$$\Delta\varepsilon_{el} = K_{ij}\left(\Delta\varepsilon_{in}\right)^{n} \tag{6}$$

Based on parallel failure lines, the strain-hardening exponent n (= b/c) in equation (6) is constant, as shown in figure 2. (The value of n can also be determined by a regression analysis using elastic and plastic PP cycling data and will usually differ somewhat from b/c.) These assumptions give enough information to determine the elastic line intercept B for cycles with time-dependent inelastic strains. Using equations (1), (2), and (6), we obtain the following relation involving both failure and flow behavior:

$$B = K_{ij}(C')^{n} \tag{7}$$

The total strainrange is the sum of the elastic and inelastic strainranges:

$$\Delta\varepsilon_{t} = \Delta\varepsilon_{el} + \Delta\varepsilon_{in} \tag{8}$$

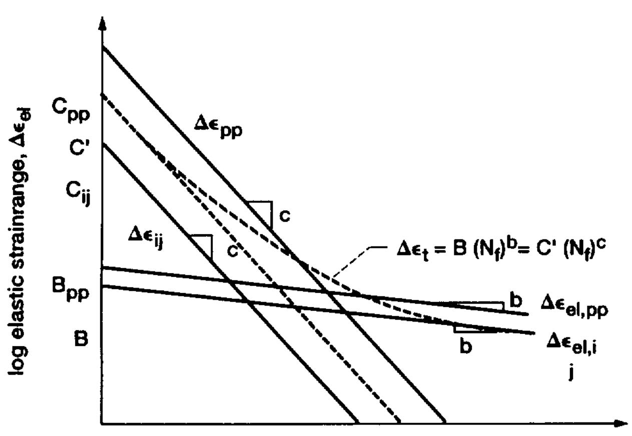


Figure 1.—Relation between total strainrange and life for creep-fatigue cycles. Inelastic line intercept C' is determined from equation (3), and elastic line intercect B is determined from equation (7).

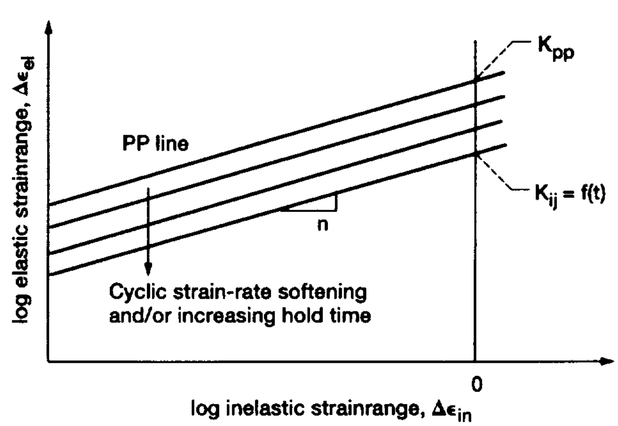


Figure 2.—Relation between inelastic and elastic strainranges for creep-fatigue cycles. Cyclic strain-hardening coefficient K_{ij} is a function of hold time and strain-rate-hardening characteristics of an alloy.

By using equations (1) and (2), the total strainrange-life equation can be obtained:

$$\Delta\varepsilon_t = B\left(N_{fo}\right)^b + C'\left(N_{fo}\right)^c \qquad (9)$$

A schematic plot of this equation is shown as a curved line in figure 1. Note that the two intercept terms, B and C', are functions of failure and flow behavior. The equivalent inelastic line intercept C' (eq. (3)) is determined by the flow terms F_{ij} and the failure terms C_{ij}; and the elastic line intercept B (eq. (7)) is determined by C' and the flow terms K_{ij} and n. The exponents b and c are considered to be failure terms.

There are two ways to determine the flow terms. The first is to use an appropriate viscoplastic constitutive flow model. This is the preferred method if a suitable model is available. The second method involves fitting test data to empirical equations. These data could come from flow tests where the phase, the manner in which time-dependent inelastic strain is produced (strain-hold, stress-hold, etc.), and the temperatures are appropriate to the cycle to be predicted. In these tests the specimen is cycled to stability, which is usually far short of failure. The method for determining stability depends to a large extent on the cyclic characteristics of the alloy (ref. 15), making it difficult to give specific recommendations. Some alloys do not achieve cyclic stability and are not amenable to flow testing, as will be shown in the next section. Data from failure tests could be used if the waveshape and temperature limits are appropriate for the duty cycle to be predicted. Note that, for a given type of cycle (CP, for example), failure behavior is usually insensitive to the manner in which time-dependent inelastic strain is produced and to temperature limits. However, flow behavior is very sensitive to these cycle parameters. There is no suitable constitutive model available for the three alloys being considered here, so we will use test data and an empirical relation first proposed in reference 5 to characterize their flow behavior.

The empirical equation is of the following form:

$$y = A'\left(\Delta\varepsilon_t\right)^{\alpha}(t)^m \qquad (10)$$

This equation is shown schematically in figure 3 and will be used here to determine correlations for F_{ij} and K_{ij}. The independent variable y in equation (10) represents the flow variable to be determined and is a function of the independent variables, total strainrange $\Delta\varepsilon_t$, and hold time per cycle t. The numerical values of the constants in equation (10) (A', α, and m) depend on the alloy, temperature, cycle type, and dependent variable being characterized. The value of α can be set to zero if desired when determining the K_{ij} correlation because this flow variable is generally insensitive to total strainrange. Dividing both sides of equation (10) by $(\Delta\varepsilon_t)^{\alpha}$ reduces the family of parallel lines shown in figure 3 to a single line, as shown in figure 4.

Appropriate failure and flow information must be available in order to predict the life of a TMF cycle on a total strain basis. For inphase cycles the required failure constants C_{pp}, C_{cp}, c, and b are determined from inphase test data. Failure behavior is generally insensitive to waveshape, so the tests used to determine the failure constants can be generic in nature. The required flow constants F_{cp} and K_{cp} must be determined by using data from tests that are representative of the duty cycle to be predicted. Similar failure and flow information is required for out-of-phase cycles except that C_{pc} is required instead of C_{cp}. The appropriate flow constants are F_{pc} and K_{pc}.

Ideally, the flow constants would be obtained from TMF test data. True TMF testing can now be done on a routine basis; however, TMF hysteresis cycles are difficult to control and analyze at lower strainranges. A viable alternative to TMF testing is bithermal testing (ref. 17). Bithermal cycles can be much easier to control and analyze, especially at lower strainranges.

Life calculations can now be made on a total strainrange basis by using equation (9) and the failure and flow information discussed in this section. The final step in a life calculation is to determine the effects of mean stress on the calculated cyclic life. Unfortunately, a proven method for determining the effects of mean stress on the life of TMF cycles is not available at this time. A method proposed by Halford (ref. 18) is based on a method first proposed for isothermal conditions:

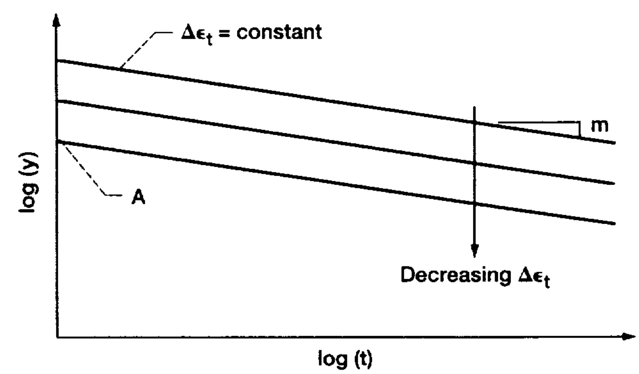


Figure 3.—Power-law relation used to correlate flow data. Lines are parallel, and intercept A at t = 1 sec is a function of total strainrange.

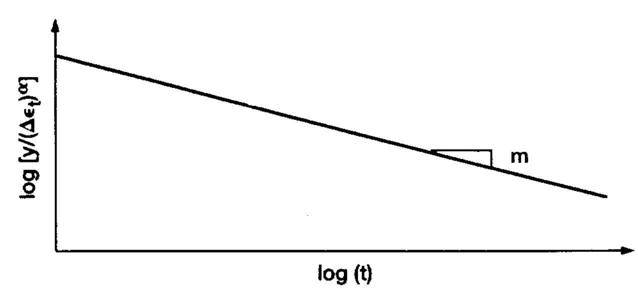


Figure 4.—Power-law normalized on total strainrange raised to suitable power, collapsing family of lines show in figure 3 into a single line. Slope will be positive for F_{ij} correlations and negative for K_{ij} correlations.

$$\left(N_{fm}\right)^{b} = \left(N_{fo}\right)^{b} - V_{\text{eff}} \tag{11}$$

where N_{fm} and N_{fo} are the cyclic lives with and without mean stress effects. The effective mean stress correction term V_{eff} is a function of the mean stress and the ratio of the inelastic and elastic strainranges. An alternate definition of V_{eff} is required for TMF conditions since a mean stress naturally develops because of the temperature variation in the TMF cycle. Halford (ref. 6) has proposed the following definition:

$$V_{\text{eff}} = \frac{1 + \dfrac{R_\sigma}{R_y}}{1 - \dfrac{R_\sigma}{R_y}} \tag{12}$$

where R_σ is equal to $\sigma_{min}/\sigma_{max}$ and R_y is the absolute value of the ratio of the compressive yield strength to the tensile yield strength at the respective maximum and minimum temperatures and strain rates in the TMF cycle. This method awaits experimental verification.

Alloy Characterization

In this section we shall discuss the characterization of the TMF failure and flow behavior of the three alloys cited in the introduction: type 304 stainless steel, 1Cr-1Mo-0.25V steel, and 2.25Cr-1Mo steel. Data for these alloys are listed in tables I to IV. These tables were generated using SRP software (ref. 9) available to the public from COSMIC (TS-SRP/PACK, Lew-15653). All testing was done in axial strain control using tubular specimens and employed fully reversed cycles with zero mean strain. The stresses and strains reported are half-life values. Most of these data are in the high-strain, low-life regime where the inelastic strainrange is the dominant part of the total strainrange. Because of the high inelastic strains, the effect of mean stress on cyclic life is nil. The elastic and inelastic strainrange PP failure relations must be established with an adequate database because subsequent failure relations (PC, CP, or CC) are forced to have the same slope. Reference 3 recommends that the cyclic lives of the PP tests cover a range of about three decades. Unfortunately, the PP lives of the alloys considered here cover a range of just over one decade.

Under ideal circumstances, flow behavior would be characterized by using data obtained at lower strainranges, where the elastic strainrange is the dominant part of the total strainrange. This is closer to the regime where most power-generating equipment operates and would help reduce extrapolation errors when predicting cyclic life.

When determining the $\Delta\varepsilon_{in}$–N_{ij} failure relations for creep cycles, it is highly desirable to have the creep damage fraction for each test be 0.50 or greater (ref. 15). All realistic TMF creep-fatigue cycles contain a PP strain component (and thus a PP damage fraction) along with the CP or PC strain component, and the two damage fractions (PP + CP (or PC)) sum to unity. In the case of the STeT cycle, there would be a PP and a CP damage fraction. The criterion of 0.50 ensures that the creep damage fraction is large enough to obtain a valid representation of this type of behavior. However, when data are limited, it is often necessary to relax this criterion.

Type 304 Stainless Steel

Two data sources (refs. 10 and 11) were used to characterize the inphase failure and flow behavior of type 304 stainless steel. These data are listed in tables I and II, respectively. Note that these sources used material from different heats with somewhat different heat treatments. The two sources were combined to characterize failure behavior because of the limited amount of data in each source. Combined data sources must have the same criterion for failure. In this case failure is defined as the number of cycles required to decrease the cyclic tensile stress to 3/4 of its half-life (steady-state) value. Caution must be used when combining data obtained from various heats and heat treatments of austenitic stainless steels because of the potential for wide variation in mechanical properties that can be caused by slight differences in chemistry and processing history.

Partitioning information is not reported for these data sources, so the following procedure was used to determine the inelastic strain components for each test. The continuous-cycling thermomechanical inphase (TMIP) tests were treated as PP cycles containing only time-independent inelastic strains ($\Delta\varepsilon_{pp}$). The frequency for these tests was only 0.0083 Hz, and the cycles likely contained a small cp strain component. However, since the magnitude of the cp component cannot be evaluated, it was ignored in the subsequent analysis. The inphase strain-hold tests (THIP) were CP-type cycles, and the $\Delta\varepsilon_{cp}$ strain component was determined by dividing the amount of the stress relaxation by the modulus of elasticity at the maximum temperature of the cycle. The remaining part of the inelastic strainrange is regarded as time-independent ($\Delta\varepsilon_{pp}$). The shortest hold-time tests (60 s) were not used to establish the CP life relation because they indicated little intergranular cracking and resembled PP rather than CP cracking modes.

Failure relations.—The SRP failure equations for inphase cycles are shown in figure 5, and the equation constants are tabulated in table V. Note that the data in reference 10 were obtained from tests with temperature limits of 550 and 200 °C, and the data from reference 11 are from tests with temperature limits of 600 and 300 °C. This difference in temperatures has only a slight effect on the failure behavior, as indicated in

TABLE I.—CREEP-FATIGUE DATA FROM REFERENCE 10 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR TYPE 304 STAINLESS STEEL

(a) Rate data and stresses

Specimen number	Test type	Temperature, °C		Rate data (half-life values)					Stresses (half-life values), MPa					
				Frequency, Hz	Strain rate, percent/sec		Hold time, sec		Tension (max)	Compression (max)	Range (max)	Relaxation		Mean amp
		Tension	Compression		Tension	Compression	Tension	Compression				Tension	Compression	
T11	TMIP	550	200	0.83×10^{-2}	3.3×10^{-2}	3.3×10^{-2}	0	0	397.2	493.3	890.5	0	0	-0.108
T12	TMIP			.83	2.5	2.5	0		381.5	471.7	853.2	0		-.106
T13	TMIP			.83	1.7	1.7	0		304.0	389.3	693.3	0		-.123
T14	THIP			.55	3.3	3.3	60		404.0	501.1	905.1	28.4		-.107
T15				.55	2.5	2.5	60		363.8	461.9	825.7	23.5		-.119
T16				.55	1.7	1.7	60		318.7	412.9	731.6	22.6		-.129
T17				.14	3.3	3.3	600		391.3	491.3	882.6	48		-.113
T18				.14	2.5	2.5	600		359.9	443.3	803.2	35.3		-.104
T19				.052	3.3	3.3	1800		379.5	472.7	852.2	71.6		-.109
T110				.027			3600		398.2	488.4	886.6	100		-.102
T01	TMOP	200	550	.83			0		485.4	436.4	921.8	0		.053
T02									481.5	424.6	906.1			.063
T03					2.5	2.5			424.6	371.7	796.3			.066
T04					1.7	1.7			353.1	299.1	652.2			.083
T05					1.7	1.7			360.9	310.9	671.8			.074
T06	CHOP			.56	3.3	3.3		60	471.7	409.9	881.6		32.4	.070
T0-S1	TMOP			.83				0	462.9	410.9	873.8		0	.060
T0-S2	TMOP			.83				0	457.0	400.1	857.1		0	.066
T0-S3	CHOP			.56				60	467.8	409.0	876.8		32.4	.067
T0-S4	CHOP			.24				300	464.9	406.0	870.9		42.2	.068
T0-S5	CHOP			.14				600	477.6	410.9	888.5		60.8	.075
T0-S6	CHOP			.052				1800	465.8	400.1	865.9		83.4	.076
I1	HRSC	550		.83				0	358.9	373.6	732.5		0	-.020
I2	HRSC			.83	2.5	2.5			326.6	341.3	667.9			-.022
I3	HRSC			.83	1.7	1.7			288.3	295.2	583.5			-.012
I4	THSC			.55	3.3	3.3	60		360.9	347.6	708.5	51		.019
I5				.55	2.5	2.5	60		325.6	339.3	664.9	34.3		-.021
I6				.55	1.7	1.7	60		288.3	298.1	586.4	17.6		-.017
I7				.24	3.3	3.3	300		360.9	374.6	735.5	49		-.019
I8				.24			300		351.1	362.9	714.0	43.2		-.017
I9				.14			600		348.1	362.9	711.0	56.9		-.021
I10				.14			600		346.2	360.9	707.1	53		-.021
I11				.052			1800		353.0	367.8	720.8	69.6		-.021
I12				.027			3600		323.6	335.4	659.0	69.6		-.018

TABLE I (Concluded).—CREEP-FATIGUE DATA FROM REFERENCE 10 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR TYPE 304 STAINLESS STEEL

(b) Strains and failure data

		Strain ranges (half-life values), percent						Failure data, cycles	
Specimen number	Total	Elastic	Inelastic	PP	PC	CP	CC	Cycles to failure	Time to failure, (hr)
T11	2.000	0.650	1.350	1.350	0	0	0	384	12.80
T12	1.500	.500	1.000	1.000		0		580	19.30
T13	1.000	.460	.540	.540		0		1615	20.50
T14	2.000	.580	1.420	1.401		.019		268	13.40
T15	1.500	.500	1.000	.984		.016		528	26.40
T16	1.000	.440	.560	.545		.015		1285	64.25
T17	2.000	.560	1.440	1.408		.032		178	-------
T18	1.500	.490	1.010	.987		.023		300	60.00
T19	2.000	.530	1.470	1.423		.047		171	91.20
T110		.520	1.480	1.414		.066		148	152.90
T01		.630	1.370	1.370		0		391	13.00
T02		.610	1.390	1.390				435	14.50
T02	1.500	.590	.910	.910				857	28.60
T04	1.000	.490	.510	.510				2136	71.20
T05	1.000	.460	.540	.540				1886	62.90
T06	2.000	.540	1.460	1.439	.021			413	20.70
T0-S1		.640	1.360	1.360	0			529	17.60
T0-S2		.640	1.360	1.360	0			566	18.87
T0-S3		.650	1.350	1.329	.021			384	19.20
T0-S4		.620	1.380	1.352	.028			417	48.65
T0-S5		.550	1.450	1.410	.040			339	67.80
T0-S6		.510	1.490	1.435	.055			[a]330	176.00
I1		.470	1.530	1.530	0			385	12.80
I2	1.500	.420	1.080	1.080				722	24.10
I3	1.000	.380	.620	.620				1727	57.60
I4	2.000	.390	1.610	1.576		.034		273	13.60
I5	1.500	.430	1.070	1.047		.023		404	20.20
I6	1.000	.380	.620	.608		.012		1221	61.10
I7	2.000	.460	1.540	1.508		.032		253	29.50
I8		.470	1.530	1.501		.028		294	34.30
I9		.460	1.540	1.503		.037		278	55.60
I10		.460	1.540	1.505		.035		308	61.60
I11		.430	1.570	1.524		.046		181	96.50
I12		.440	1.560	1.514		.046		171	176.70

[a]Did not fail.

TABLE II.—CREEP-FATIGUE DATA FROM REFERENCE 11 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR TYPE 304 STAINLESS STEEL

(a) Rate data and stresses

Specimen number	Test type	Temperature, °C		Rate data (half-life values)					Stresses (half-life values), MPa					
				Frequency, Hz	Strain rate, percent/sec		Hold time, sec		Tension (max)	Compression (max)	Range (max)	Relaxation		Mean amp
		Tension	Compression		Tension	Compression	Tension	Compression				Tension	Compression	
IT1	TMIP	600	300	0.83×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	0	0	369.6	444.7	814.3	0	0	-0.092
IT2	TMIP				1.7	1.7			304.1	370.9	675.0			-.099
IT3	TMIP				1.3	1.3			283.1	340.0	623.1			-.091
IT4	TMIP				.92	.92			250.0	320.1	570.1			-.123
IT5	LRIP			.17	.25	.25	300.0	300.0	359.2	421.6	780.8			-.080
IT6	THIP			.17	2.5	2.5	480.0	0	310.2	376.1	686.3	71.7		-.096
IT7	LRIP			.083	.25	.25	600.0	600.0	354.3	415.5	769.8	0		-.080
IT8	THIP			.083	2.5	2.5	1080.0	0	298.4	362.3	660.7	79.6		-.097
OT1	TMOP	300	600	.83	2.5	2.5	0		391.6	347.8	739.4	0		.059
OT2	TMOP				2.5	2.5			353.9	307.9	661.8			.070
OT3	TMOP				2.5	2.5			338.1	294.8	632.9			.068
OT4	TMOP				2.5	2.5			299.2	255.0	554.2			.080
OT5	LROP			.17	.25	.25	300.0	300.0	404.4	349.5	753.9			.073
OT6	CHOP			.17	.5	.5	0	480.0	357.5	306.0	663.5		61.9	.078
OT7	LROP			.083	.25	.25	600.0	600.0	408.2	354.8	763.0		0	.070
OT8	CHOP			.083	.25	.25	0	1080.0	343.3	287.6	630.9		68.8	.088

TABLE II (Concluded).—CREEP-FATIGUE DATA FROM REFERENCE 11 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR TYPE 304 STAINLESS STEEL

(b) Strains and failure data

		Strain ranges (half-life values), percent						Failure data	
Specimen number	Total	Elastic	Inelastic	PP	PC	CP	CC	Cycles to failure	Time to failure, hr
IT1	1.500	0.550	0.950	0.950	0	0	0	488	16.30
IT2	1.000	.470	.530	.530				1033	34.40
IT3	.800	.410	.390	.390				1688	56.30
IT4	.550	.360	.190	.190				3990	133.00
IT5	1.500	.470	1.030	.914			.116	362	60.30
IT6		.420	1.080	1.032		.048	.000	238	39.70
IT7		.490	1.010	.857		.000	.153	289	96.30
IT8		.370	1.130	1.077		.053	.000	245	81.60
OT1		.540	.960	.960		.000		731	24.40
OT2	1.000	.460	.540	.540				1361	45.40
OT3	.800	.400	.400	.400				1946	64.90
OT4	.550	.320	.230	.230				3437	114.60
OT5	1.500	.530	.970	.862			.108	852	142.00
OT6		.410	1.090	1.049	.041		.000	638	106.30
OT7		.500	1.000	.736	.000		.264	517	172.30
OT8		.430	1.070	1.024	.046		.000	651	216.80

TABLE III.—CREEP-FATIGUE DATA FROM REFERENCE 12 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR 1Cr–1Mo–0.25V STEEL

(a) Rate data and stresses

Specimen number	Test type	Temperature, °C		Rate data (half-life values)					Stresses (half-life values), MPa					
				Frequency, Hz	Strain rate, percent/sec		Hold time, sec		Tension (max)	Compression (max)	Range (max)	Relaxation		Mean amp
		Tension	Compression		Tension	Compression	Tension	Compression				Tension	Compression	
CR-IN1	TMIP	550	300	$.83\times10^{-2}$	2.5×10^{-2}	2.5×10^{-2}	0	0	418.7	590.3	1009.0	0	0	-0.170
CR-IN2	TMIP				2.5	2.5			428.5	597.2	1025.7			-.164
CR-IN3	TMIP				1.7	1.7			386.4	556.0	942.4			-.180
CR-IN4	TMIP				1.7	1.7			384.4	548.2	932.6			-.176
CR-IN5	TMIP				1.3	1.3			351.0	520.7	871.7			-.195
CR-IN6	TMIP				1.3	1.3			357.9	522.7	880.6			-.187
CR-IN7	TMIP				.83	.83			313.8	483.4	797.2			-.213
CR-IN8	THIP			.42	2.5	2.5	120		406.0	603.0	1009.0	117.7		-.195
CR-IN9	THIP			.14			600		394.2	588.4	982.6	140.2		-.198
CR-IN10	THIP			.052			1800		366.7	563.8	930.5	150.0		-.212
CR-IN11	THIP			.027			3600		374.6	571.7	946.3	163.8		-.208
CR-IN12	THIP			.42	1.7	1.7	120		363.8	563.8	927.6	85.3		-.216
CR-IN13	THIP			.14	1.7	1.7	600		356.9	558.9	915.8	108.8		-.221
CR-IN14	THIP			.42	1.3	1.3	120		316.7	523.6	840.3	78.4		-.246
CR-IN15	THIP			.14	1.3	1.3	600		316.7	523.6	840.4	88.3		-.246
CR-IN16	TMIP			.012	5.0	5.0	0		407.9	570.1	978.0	0		-.166
CR-IN17	TMIP			.14	4.2	.42			387.3	571.7	959.0			-.192
CR-IN18	TMIP			.052	1.6	.16			384.4	574.6	959.0			-.198
CR-OT1	TMOP	300	550	.83	2.5	2.5			554.1	466.8	1020.9			.086
CR-OT2	TMOP			.42	2.5	2.5			558.0	419.7	977.8			.141
CR-OT3	TMOP			.14	1.7	1.7			528.6	388.4	917.0			.153
CR-OT2	TMOP			.052	1.7	1.7			507.0	371.7	878.7			.154
CR-OT5	TMOP			.027	1.7	1.7			541.3	397.2	938.5			.154
CR-OT6	TMOP			.42	1.3	1.3			502.1	363.8	866.0			.160
CR-OT7	TMOP			.64	1.3	1.3			511.9	376.6	888.5			.152
CR-OT8	TMOP				1.0	1.0			496.2	349.1	845.4			.174
CR-OT9	TMOP				.83	.83			447.2	356.0	803.2			.114

TABLE III (Concluded).—CREEP-FATIGUE DATA FROM REFERENCE 12 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR 1Cr-1Mo-0.25V STEEL

(b) Strains and failure data

		Strain ranges (half-life values), percent						Failure data	
Specimen number	Total	Elastic	Inelastic	PP	PC	CP	CC	Cycles to failure	Time to failure, hr
CR-IN1	1.500	0.550	0.950	0.950	0	0	0	453	15.10
CR-IN2	1.500	.530	.970	.970				486	16.20
CR-IN3	1.000	.499	.501	.501				1041	34.70
CR-IN4	1.000	.483	.517	.517				968	32.20
CR-IN5	.800	.473	.327	.327				2065	68.83
CR-IN6	.800	.477	.323	.323				2082	69.40
CR-IN7	.500	.425	.075	.075		↓		6505	216.83
CR-IN8	1.500	.468	1.032	.957		.075		353	23.50
CR-IN9		.476	1.024	.935		.089		286	57.20
CR-IN10		.458	1.042	.947		.095		321	171.20
CR-IN11	↓	.440	1.060	.956		.104		202	208.70
CR-IN12	1.000	.437	.563	.509		.054		718	47.90
CR-IN13	1.000	.429	.571	.502		.069		583	116.60
CR-IN14	.800	.429	.371	.321		.050		1391	92.70
CR-IN15	.800	.404	.396	.340		.056		826	165.20
CR-IN16	1.500	.534	.966	.966		.000		512	8.50
CR-IN17		.518	.982	.982				554	110.80
CR-IN18		.502	.998	.998				477	254.40
CR-OT1		.545	.955	.955				489	16.30
CR-OT2	↓	.510	.990	.990				389	12.90
CR-OT3	1.000	.522	.478	.478				739	24.60
CR-OT2	1.000	.506	.494	.494				911	30.40
CR-OT5	1.000	.510	.490	.490				899	30.00
CR-OT6	.800	.484	.316	.316				1243	41.40
CR-OT7	.800	.490	.310	.310				1113	37.10
CR-OT8	.600	.455	.145	.145				1977	65.90
CR-OT9	.500	.432	.068	.068	↓	↓	↓	4258	141.90

TABLE IV.—CREEP-FATIGUE DATA FROM REFERENCE 13 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR 2.25Cr–1Mo STEEL

(a) Rate data and stresses

Specimen number	Test type	Temperature, °C		Rate data (half-life values)					Stresses (half-life values), MPa					
				Frequency, Hz	Strain rate, percent/sec		Hold time, sec		Tension (max)	Compression (max)	Range (max)	Relaxation		Mean amp
		Tension	Compression		Tension	Compression	Tension	Compression				Tension	Compression	
7101	TMIP	538	300	$.83\times10^{-2}$	2.5×10^{-2}	2.5×10^{-2}	0	0	254.0	303.0	557.0	0	0	-0.088
7100					1.7	1.7			235.4	288.3	523.7			-.101
7102					1.3	1.3			221.6	276.6	498.2			-.110
7103					.91	.91			191.2	246.2	437.4			-.126
8103					2.5	2.5			231.4	268.7	500.2			-.075
8102					1.7	1.7			236.3	282.4	518.8			-.089
8101					1.3	1.3			225.6	279.5	505.1			-.107
8100					.91	.91			206.1	264.3	470.4			-.124
8104					.91	.91			187.3	239.3	426.6			-.122
7104	THIP			.14	2.5	2.5	600		256.0	313.8	569.8	116.7		-.101
8108	THIP			.14	2.5	2.5	600		230.5	279.5	510.0	117.7		-.096
7105	THIP			.56	.91	.91	60		190.3	256.9	447.2	38.2		-.149
IT03	SFIP	600	360	.30	.25	.25	300	30	213.8	282.4	496.2	0		-.138
IT02	SFIP	600	360	.30	1.3	.13	300	30	169.7	248.1	417.8			-.188
IT01	SFIP	600	360	.30	.92	.92	300	30	149.1	222.6	371.7			-.198
7202	TMOP	300	538	.83	2.5	2.5	0	0	290.3	247.1	537.4			.080
7203					2.5	2.5			298.1	251.1	549.2			.086
7200					1.7	1.7			273.6	226.5	500.2			.094
7201					1.3	1.3			250.1	202.0	452.1			.106
7204					.91	.91			240.3	189.3	429.5			.119
8203					2.5	2.5			258.9	219.7	478.6			.082
8201					1.7	1.7			262.8	216.7	479.6			.096
8209					1.7	1.7			267.7	221.6	489.4			.094
8202					1.3	1.3			239.3	196.1	435.4			.099
8200					.91	.91			245.2	194.2	439.4			.116
8205	CHOP			.17	2.5	2.5		600	269.7	223.6	493.3	102.0		.093
7205	CHOP			.17	2.5	2.5		600	295.2	238.3	533.5	112.8		.107
7206	CHOP			.56	.91	.91		60	220.7	173.6	394.2	0	41.2	.119
0T03	FSOP	360	600	.3	3.3	1.7×10^{-3}	30	600	235.4	176.5	411.9	0	0	.143
0T02	FSOP	360	600	.3	2.7	1.3	30	600	224.6	170.6	395.2	0	0	.137
0T01	FSOP	360	600	.3	1.8	.92	30	300	199.1	146.1	345.2	0	0	.154

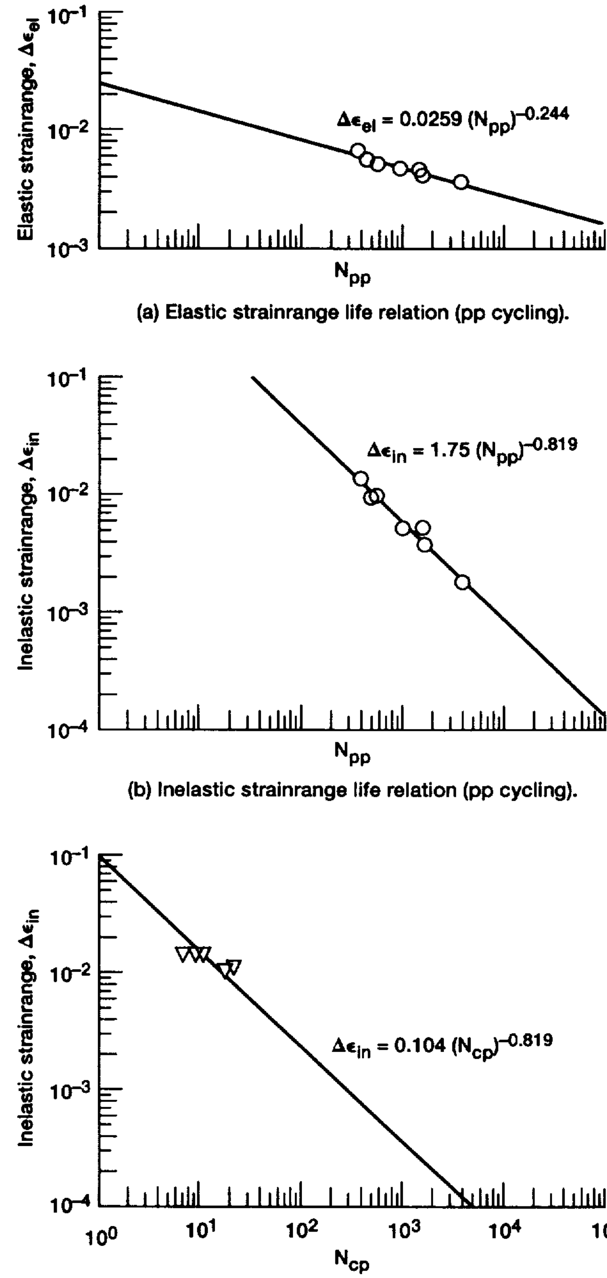
TABLE IV (Concluded).—CREEP-FATIGUE DATA FROM REFERENCE 13 USED TO DETERMINE TMF FAILURE AND FLOW RELATIONS FOR 2.25Cr-1Mo STEEL

(b) Strains and failure data

		Strain ranges (half-life values), percent						Failure data	
Specimen number	Total	Elastic	Inelastic	PP	PC	CP	CC	Cycles to failure	Time to failure, hr
7101	1.500	0.282	1.218	1.177	0	0.041	0	448	14.90
7100	1.000	.271	.729	.707		.023		1046	34.90
7102	.800	.262	.538	.492		.046		1650	55.00
7103	.550	.235	.315	.313		.002		4190	39.70
8103	1.500	.251	1.249	1.249		.000		413	13.80
8102	1.000	.271	.729	.729				1000	33.30
8101	.800	.268	.532	.532				1627	54.20
8100	.550	.228	.322	.322				2864	95.47
8104	.550	.222	.328	.328				4612	153.70
7104	1.500	.251	1.249	1.121		.128		338	67.60
8108	1.500	.207	1.293	1.197		.096		374	72.80
7105	.550	.228	.322	.295		.027		3830	191.50
IT03	1.500	.224	1.276	1.141		.135		325	29.80
IT02	.800	.223	.577	.541		.036		906	83.10
IT01	.550	.190	.360	.345		.014		1648	151.00
7202	1.500	.273	1.227	1.227		.000		707	23.60
7203	1.500	.289	1.211	1.211				658	21.90
7200	1.000	.278	.722	.722				1018	33.90
7201	.800	.240	.560	.560				1300	43.30
7204	.550	.226	.324	.324				2248	74.90
8203	1.500	.244	1.256	1.256				850	28.30
8201	1.000	.242	.758	.758				1120	37.30
8209	1.000	.263	.737	.737				947	31.60
8202	.800	.231	.569	.569				1667	55.60
8200	.550	.247	.303	.303				2265	75.50
8205	1.500	.208	1.292	1.209	.083			379	75.80
7205	1.500	.231	1.269	1.154	.114			456	91.20
7206	.550	.190	.360	.332	.027			2030	101.50
OT03	1.000	.237	.763	.688	.075			853	78.18
OT02	.800	.226	.574	.525	.048			998	91.48
OT01	.550	.212	.338	.319	.019			1478	135.48

figure 5. Failure relations for out-of-phase hold-time cycles were not determined because these cycles exhibited little life loss compared to the out-of-phase no-hold tests.

Flow relations.—The relations for the flow variables F_{cp} and K_{cp} and the ability of equation (10) to correlate the data from reference 10 are shown in figures 6 and 7, respectively. The equation constants for F_{cp} are tabulated in table VI, and the equation constants for K_{cp} are tabulated in table VII. Note that the 60-s hold-time data were not used, as noted previously. The equation constants are appropriate only for tensile-hold in-phase (THIP) cycles between the temperature limits of 200 and 550 °C. The value of n (0.297) used to determine K_{cp} was obtained by using the values of b (−0.244) and c (−0.819) shown in figure 5 (and table V). Since flow behavior is very sensitive to temperature, the data from reference 11 were not used because of the different temperatures (300 and 600 °C).



(a) Elastic strainrange life relation (pp cycling).

(b) Inelastic strainrange life relation (pp cycling).

(c) Inelastic strainrange life relation (cp cycling).

Figure 5.—Failure relations for inphase thermomechanical fatigue cycles (200 ↔ 550 °C) for type 304 stainless steel (data from refs. 10 and 11).

1Cr-1Mo-0.25V Steel

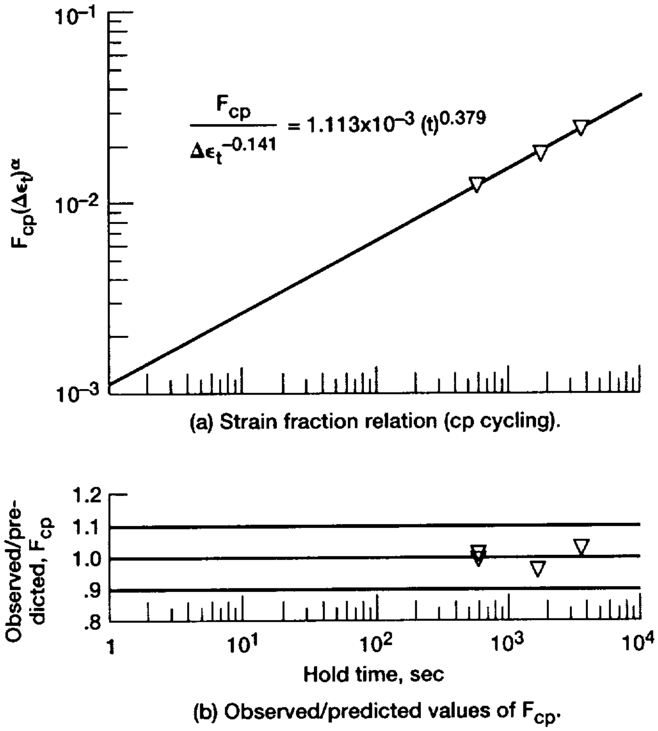
Data for 1Cr-1Mo-0.25V steel (table III) are from reference 12 and are for inphase continuous cycles (TMIP) and inphase tensile strain-hold (THIP) cycles with maximum and minimum temperatures of 550 and 300 °C, respectively. The specimens were taken from a high-pressure steam turbine rotor forging and were in a normalized and tempered condition. Partitioning data were not reported for these data, so partitioning was done as described for type 304 stainless steel. Failure is defined as the number of cycles for the maximum tensile stress to decline to 3/4 of its half-life (steady-state) value.

Failure relations.—The SRP failure relations for inphase cycles are shown in figure 8, and the equation constants are tabulated in table V. Only one of the eight THIP tests has a *CP* damage fraction (0.615) that meets the criterion of 0.50, so the criterion was relaxed to 0.44 giving four data points to determine the $\Delta\varepsilon_{in}$-N_{cp} failure relation.

Flow relations.—The equations for the flow variables F_{cp} and K_{cp} and their ability to correlate the data are shown in figures 9 and 10, respectively, while the equation constants are tabulated in tables VI and VII, respectively. For many alloys, flow testing is a viable way to determine the constants in equation (10) for a cycle of interest. But for this alloy, flow testing does not appear to be a useful concept because of the considerable cyclic strain softening over the entire life of the test, as shown in figures 11 and 12.

2.25Cr-1Mo Steel

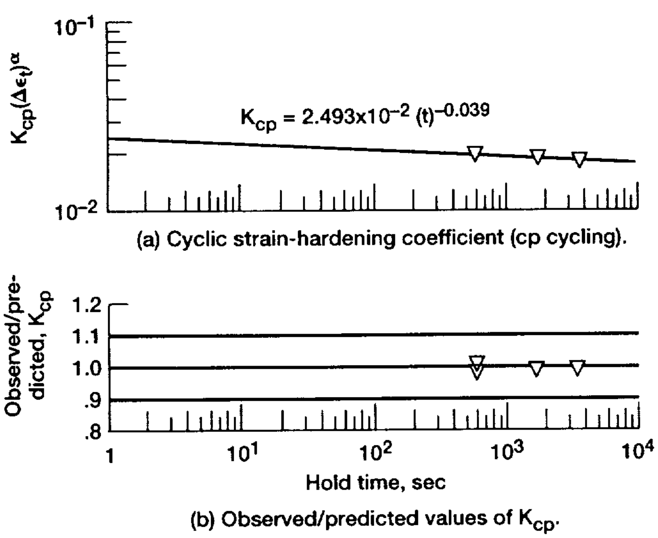
The data for 2.25Cr-1Mo steel (refs. 13 and 14) were obtained by using specimens taken from a section of a main steam pipe of a thermal power plant that had been operating for about 130 000 hr at a temperature of 538 °C and a pressure of 148 atm and for 426 duty cycles. The initial heat treatment is not known, but the microstructure suggests annealing and tempering (ref. 14). The specimens were taken from the pipe in the longitudinal and circumferential direction. The longitudinal specimens are identified by a 7XXX series number, and the circumferential specimens are identified by an 8XXX number



(a) Strain fraction relation (cp cycling).

(b) Observed/predicted values of F_{cp}.

Figure 6.—Relations between F_{cp} and hold time for tensile-hold inphase (THIP) thermomechanical fatigue cycles (200 ↔ 550 °C) for type 304 stainless steel (data from ref. 10).



(a) Cyclic strain-hardening coefficient (cp cycling).

(b) Observed/predicted values of K_{cp}.

Figure 7.—Relations between K_{cp} and hold time for tensile-hold inphase (THIP) thermomechanical fatigue cycles (200 ↔ 550 °C) for type 304 stainless steel (data from ref. 10).

TABLE V.—TMF FAILURE EQUATION CONSTANTS

Alloy	C_{pp}	C_{cp}	C_{pc}	B	c	b
304 Stainless Steel	1.75	0.104	-------	0.0259	-0.819	-0.244
1Cr-Mo-0.25V	3.58	.499	-------	.0093	-.945	-.090
2.25Cr-1Mo	33.27	------	2.672	.0143	-1.201	-.246

TABLE VI.—TMF EQUATION CONSTANTS FOR F_{cp}

[$F_{cp} = A' (\Delta\epsilon_t)^{\alpha} (t)^m$.]

Alloy	A'	α	m
304 Stainless Steel	1.113×10^{-3}	-0.141	0.379
1Cr-Mo-0.25V	1.21×10^{-3}	-0.874	.088
2.25Cr-1Mo	------------	------	-------

TABLE VII.—TMF EQUATION CONSTANTS FOR K_{cp}

[$K_{cp} = A' (\Delta\epsilon_t)^{\alpha} (t)^m$.]

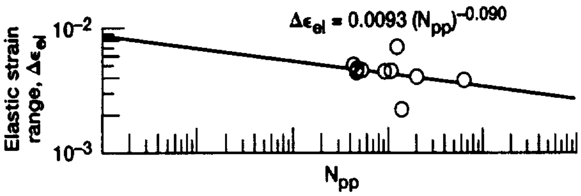
Alloy	A'	α	m
304 Stainless Steel	24.93×10^{-3}	0.0	-0.039
1Cr-1Mo-0.25V	9.921×10^{-3}	.048	-.020
2.25Cr-1Mo	-------------	------	--------

(see table IV). There are no discernible differences in the failure behavior of the longitudinal and circumferential specimens. Partitioning of these tests was done using the Step Stress method (ref. 19) and is reported in table 4.5 of reference 14. Inphase and out-of-phase tests were done. The continuous-cycling tests (TMIP, TMOP) and the strain-hold tests (THIP, CHOP) were performed with temperature limits of 300 and 538 °C. The dual-rate, continuously cycled tests (SFIP, FSOP) had temperature limits of 360 and 600 °C.

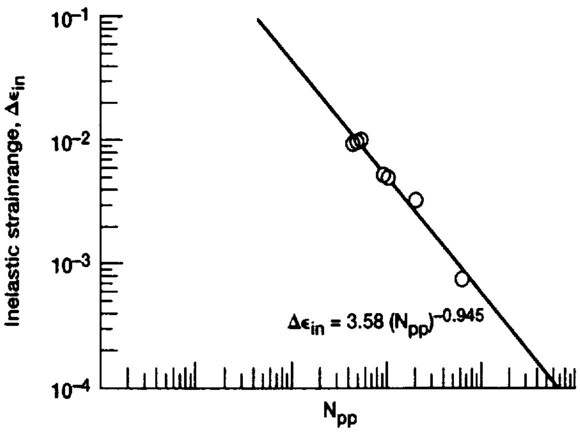
Failure relations.—The SRP failure relations for out-of-phase cycles are shown in figure 13 and the equation constants tabulated in table V. Failure is defined as the number of cycles required for the cyclic tensile stress to reduce to 3/4 of the half-life (steady-state) value. The $\Delta\varepsilon_{in}$-N_{pc} failure relation was determined by combining the data for the CHOP and FSOP tests. The differences in temperatures were judged to have a negligible effect on cyclic life. Again, it was necessary to relax the damage fraction criterion of 0.50. In this case it was relaxed to 0.33, giving a total of four PC data points.

The data from the inphase tests do not permit the determination of an adequate $\Delta\varepsilon_{in}$-N_{cp} failure relation. The THIP and SFIP data were combined ignoring the temperature differences (see table IV), giving a total of six CP data points. None of these data satisfied the damage fraction criterion of 0.50, and only two had a CP damage fraction greater than 0.40. The damage fraction of the remaining four tests ranged from 0.100 to 0.261. Thus the data were judged to be inadequate for our purposes.

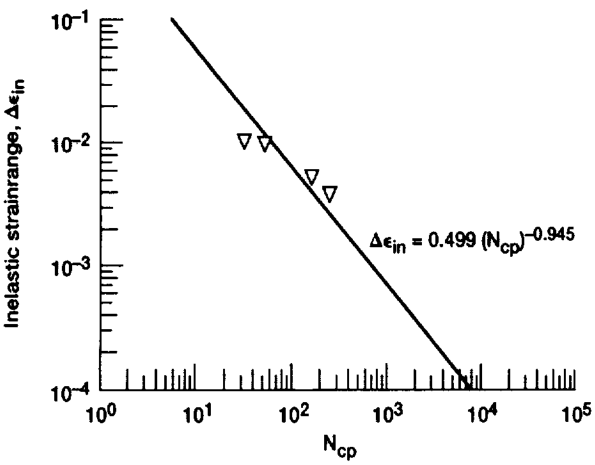
Flow relations.—The data do not permit the establishment of the F_{pc} and the K_{pc} flow relations using equation (10). Life calculations for this alloy will be made using flow information in table IV.



(a) Elastic strainrange life relation (pp cycling).



(b) Inelastic strainrange life relation (pp cycling).

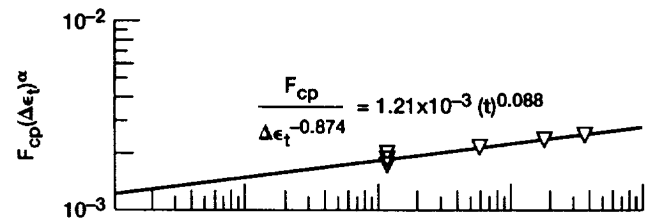


(c) Inelastic strainrange life relation (cp cycling).

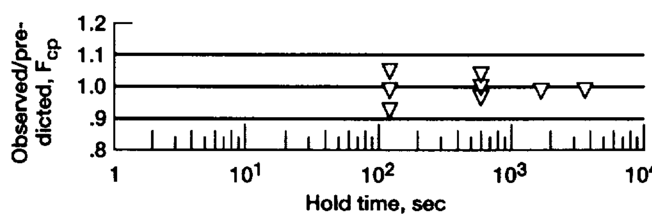
Figure 8.—Failure relations for inphase thermomechanical fatigue cycles (300 ⟷ 550 °C) for 1Cr–1Mo–0.25V steel (data from ref. 12).

Life Prediction

In this section we evaluate in a limited way the ability of TS-SRP to predict the life of TMF cycles on a total strain basis using the failure and flow correlations determined in the preceding section. Unfortunately, the data used in the predictions are the same data used to determine these correlations. It is obvious that they will not be true predictions but are an "echo"

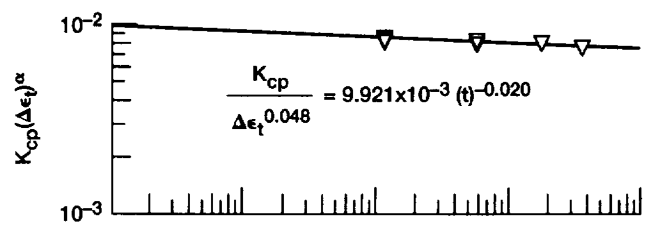


(a) Strain-fraction relation (cp cycling).

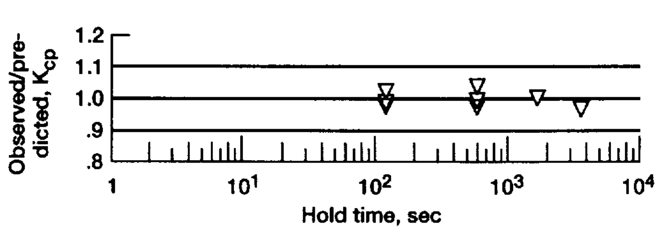


(b) Observed/predicted values of F_{cp}.

Figure 9.—Relations between F_{cp} and hold time for tensile-hold inphase (THIP) thermomechanical fatigue cycles (300 ⟷ 550 °C) for 1Cr–1Mo–1V steel (data from ref. 12).



(a) Cyclic strain-hardening coefficient (cp cycling).



(b) Observed/predicted values of K_{cp}.

Figure 10.—Relations between K_{cp} and hold time for tensile-hold inphase (THIP) thermomechanical fatigue cycles (300 ⟷ 550 °C) for 1Cr–1Mo–0.25V steel (data from ref. 12).

of the data used in the correlations and will give an indication of the background scatter one might expect when predicting life.

Cyclic life is calculated by determining the value of the inelastic line intercept C' and the elastic line intercept B in equation (9) for the cycle of interest. The values of C' and B are determined by using equations (3) and (7), respectively. The flow terms F_{ij} and K_{ij} should be determined from tests with a wave shape and temperature limits appropriate for the duty cycle to be predicted. The intercept values C' and B and the exponents c and b are then used with equation (9) and the known value of the total strainrange to calculate the life of the duty cycle of interest. These calculations were made with the appropriate failure and flow equation constants listed in tables V to VII. Note that the calculated life is for a theoretical zero mean stress condition. Equation (9) can be solved in an iterative manner or a direct solution can be obtained using Manson's inversion method (ref. 20). We have used the inversion method.

The final step in making a life prediction is to adjust the calculated life to account for mean stress effects under TMF loading. Generally, a tensile mean stress will reduce cyclic life whereas a compressive mean stress will increase life. As noted

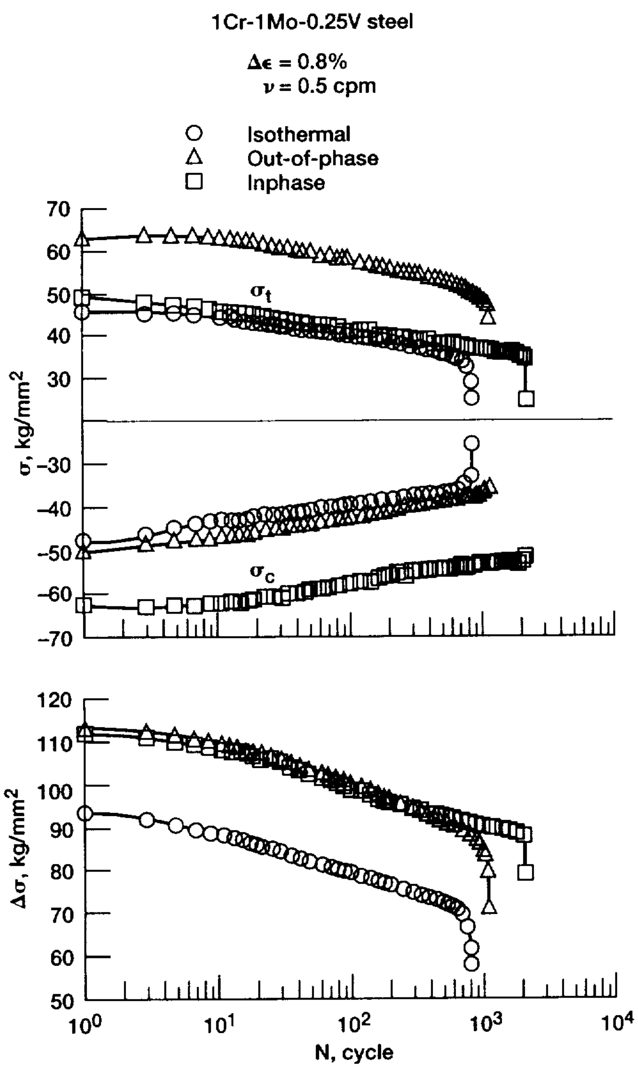


Figure 11.—Softening behavior of 1Cr-1Mo-0.25V steel without hold time for isothermal (550 °C), inphase, and out-of-phase cycles (300 ⇄ 550 °C), with total strainrange of 0.8 percent and frequency of 0.5 Hz (taken from ref. 12).

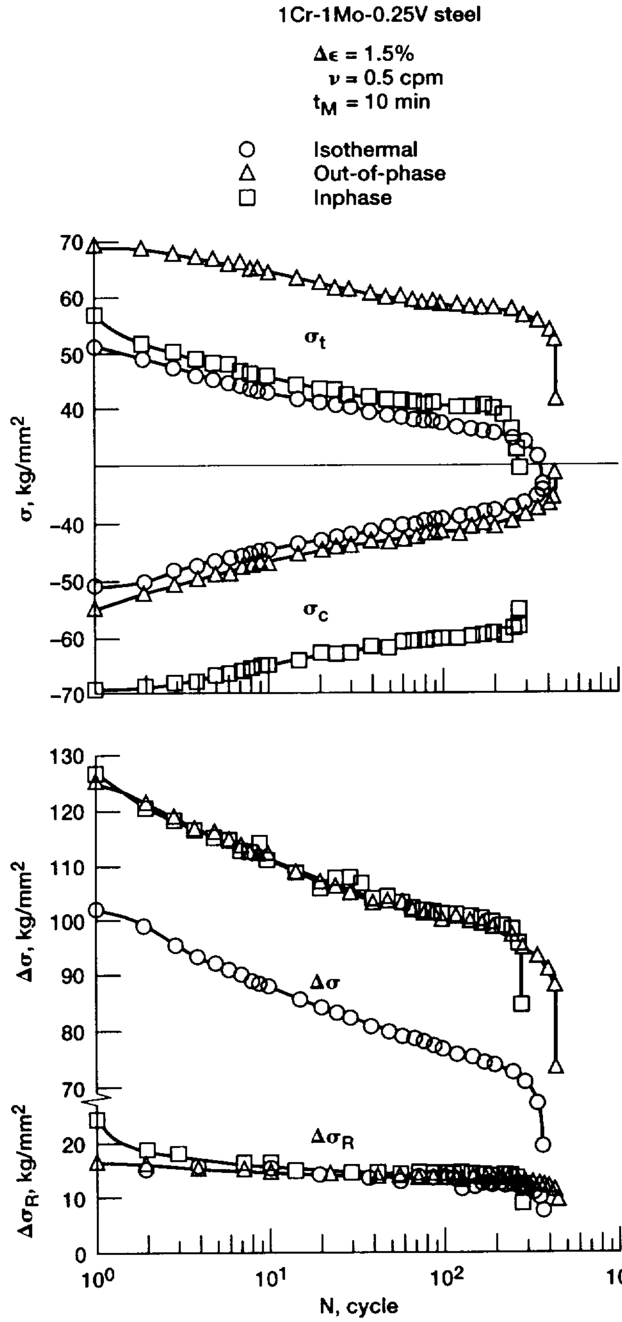
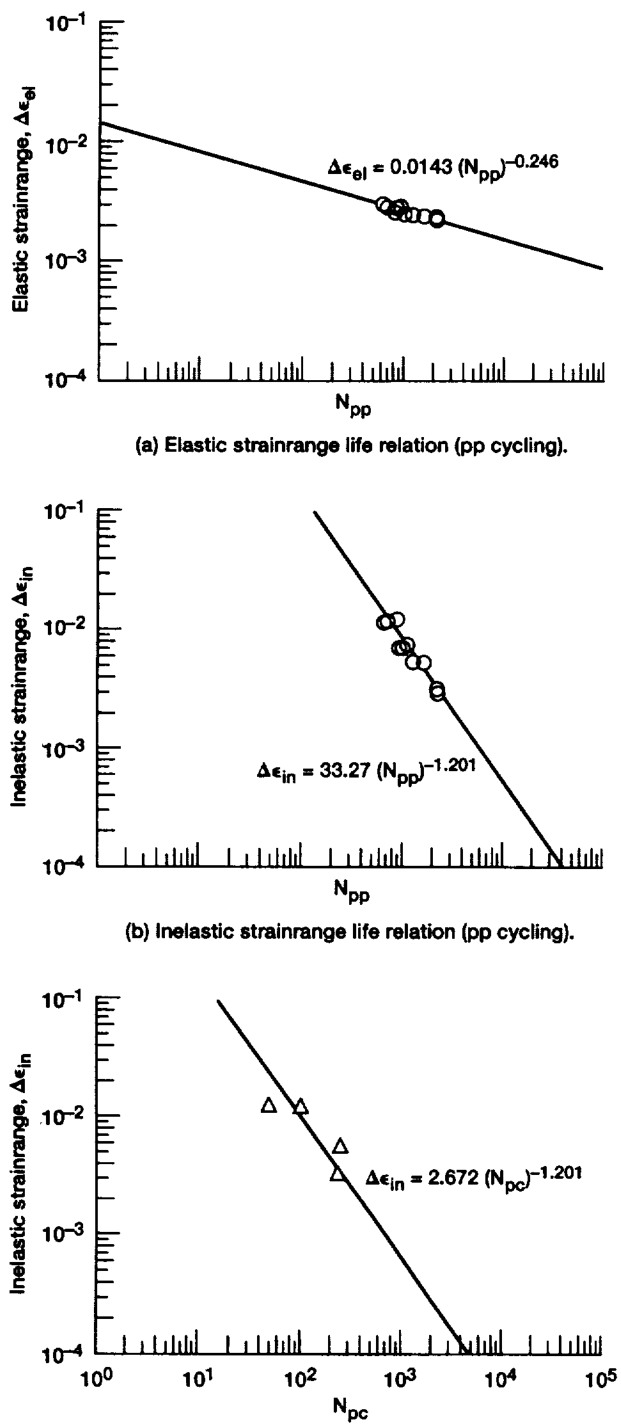


Figure 12.—Softening behavior of 1Cr-1Mo-0.25V steel with 10-min hold time for isothermal (500 °C), inphase, and out-of-phase cycles (300 ⇄ 550°C), with total strainrange of 1.5 percent (taken from ref. 12).

in the preceding section, there is no verified way at present to account for mean stress effects under TMF loading. However, the mean stress effects are expected to be nil for these data because of the high total strainranges and the high ductility of the alloys. The results of the life calculations for the three alloys considered herein are listed in table VIII and are discussed in the following subsections.



(a) Elastic strainrange life relation (pp cycling).

(b) Inelastic strainrange life relation (pp cycling).

(c) Inelastic strainrange life relation (pc cycling).

Figure 13.—Failure relations for out-of-phase thermomechanical fatigue cycles (300↔538 °C) for 2.25Cr–1Mo steel (data from refs. 10 and 11).

Type 304 Stainless Steel

As noted earlier, data from two sources (refs. 10 and 11) were combined to determine the failure correlations. It is appropriate at this point to determine if this was justified. A plot of calculated versus observed lives for the TMIP cycles used to determine the PP inelastic and elastic life relations is shown in figure 14. There may be slight differences in the fatigue properties of the two sources because of the different temperatures and heats but they appear similar enough to justify combining the data. A good PP failure line is important because the subsequent failure lines (CP or PC) are forced to have the same slope.

Life calculations were made for the THIP tests used to determine the $\Delta\varepsilon_{in}$-N_{cp} life relation (fig. 5(c)). These tests feature a tension hold time of 600 s or greater. The life reduction for the 60-s hold-time tests (see table I) was minimal because of the small amount of intergranular cracking present (ref. 10). The flow correlations for F_{cp} and K_{cp} (figs. 6 and 7) were used to calculate the lives of the data from reference 10, while the lives of the two THIP tests in reference 11 were calculated using values of F_{cp} and K_{cp} determined using flow data from table II. As noted earlier, flow behavior is sensitive

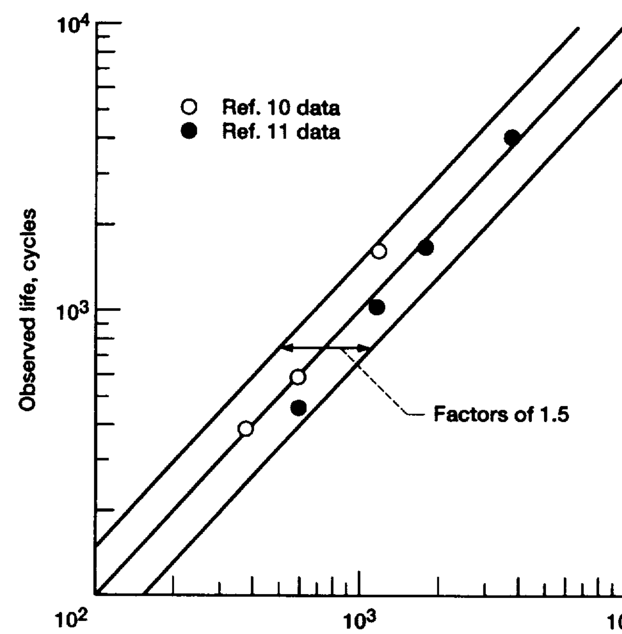


Figure 14.—Plot of observed versus calculated cyclic life of inphase test data used to determine the elastic and inelastic PP life relations for type 304 stainless steel (data from refs. 10 and 11).

to temperature, so the flow correlations for THIP cycles obtained from the data in reference 10 should not be used to predict the THIP tests in reference 11. The scatter in these life calculations is well within factors of 1.5 on cyclic life.

1Cr-1Mo-0.25V Steel

Life calculations were made for the THIP tests used to determine the $\Delta\varepsilon_{in}$-N_{cp} relation (fig. 8(c)). The scatter for these calculations is within factors of 1.5 on cyclic life for all but one test.

2.25Cr-1Mo Steel

Life calculations were made for the out-of-phase CHOP and FSOP cycles used to determine the $\Delta\varepsilon_{in}$-N_{cp} life relation (fig. 13(c)). Flow correlations could not be determined for this alloy, so test data (table IV) were used to obtain the flow variables F_{pc} and K_{pc} needed to calculate the intercepts C' and B. Again, the scatter in these life calculations is within a factor of 1.5 on cyclic life for all but one test.

The lives of 20 TMF creep-fatigue tests have been calculated, and 18 (or 90 percent) agree with observed lives within factors of 1.5 on cyclic life as shown in figure 15. An examination of table VIII and figure 15 shows a slight conservative bias to the life calculations, with 13 of the 20 (65 percent) calculations being conservative.

Concluding Remarks

The total strain version of strainrange partitioning (TS-SRP) was first developed for isothermal conditions. Later, a method was proposed to extend TS-SRP to thermomechanical fatigue cycles. This extension lacked experimental verification, but in a subsequent paper, TMF data for two high-temperature aerospace alloys were used to demonstrate the viability of extending TS-SRP to TMF conditions. In this report, we have shown that it can also be applied to TMF data for three low-strength, high-ductility alloys commonly used in ground-based, power-generating equipment. Using these data, we were able to characterize both the failure and flow behavior of the alloys.

Life predictions were made for the same data used to determine the failure and flow correlations to illustrate the correlative and predictive capabilities of the method. These are not true predictions, but are an "echo" because these same data were used to determine the failure and flow correlations used to make the predictions. The lives of 20 TMF creep-fatigue data points were calculated, and 18 (or 90 percent) agreed with experimental results within factors of 1.5 on cyclic life, giving a measure of the ability of TS-SRP to characterize both failure and flow behavior. It was not possible to make true predictions because of the limited amount of data.

TABLE VIII.—SUMMARY OF LIFE CALCULATIONS

Alloy	Reference	Specimen number	Cycle type	$\Delta\varepsilon_t$, percent	Hold time, sec	Observed life	Calculated life	Observed/calculated life
304 Stainless Steel	10	T17	THIP	2.0	600	178	202	0.881
		T18[a]	THIP	1.5	600	300	282	1.064
		T19	THIP	2.0	1800	171	176	.972
		TI10	THIP	2.0	3600	148	159	.931
	11	IT6	THIP	1.5	480	238	212	1.123
		IT8	THIP	1.5	1080	245	194	1.263
1Cr-1Mo-0.25V	12	CR-IN8[a]	THIP	1.5	120	353	345	1.023
		CR-IN9	THIP	1.5	600	286	323	.885
		CR-IN10[a]	THIP	1.5	1800	321	308	1.042
		CR-IN11	THIP	1.5	3600	202	299	.676
		CR-IN12[a]	THIP	1.0	120	718	586	1.225
		CR-IN13	THIP	1.0	600	583	512	1.139
		CR-IN14[a]	THIP	.8	120	1391	744	1.871
		CR-IN15	THIP	.8	600	826	676	1.222
2.25Cr-1Mo	14	8205	CHOP	1.5	600	379	462	0.822
		7205	CHOP	1.5	600	456	418	1.091
		7206[a]	CHOP	---	60	2030	1305	1.556
		OT03	CHOP	1.0	600	853	625	1.365
		OT02	FSOP	.8	600	998	848	1.177
		OT01	FSOP	.55	300	1478	1507	.981

[a]Data not used to determine $\Delta\varepsilon_{in}$ - N_{ij} failure correlation because of low damage fraction.

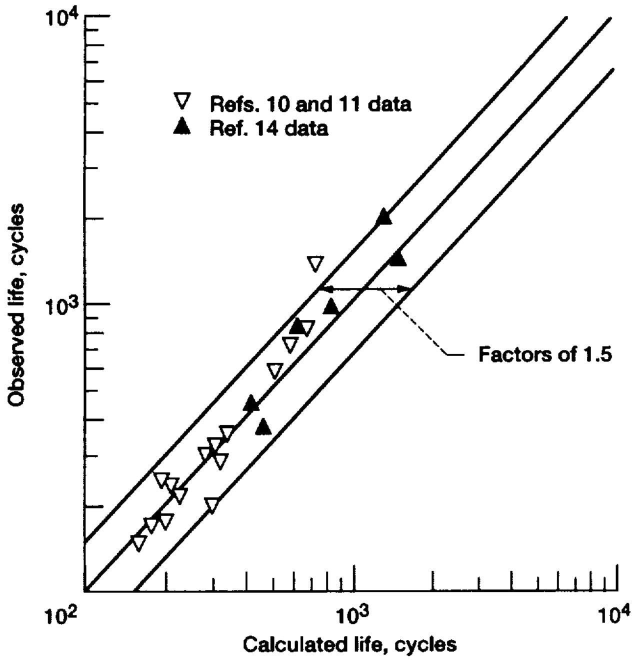


Figure 15.—Plot of observed versus calculated life of all test data used to determine the time-dependent failure relations.

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13. ABSTRACT *(Maximum 200 words)*

Strainrange partitioning (SRP) was originally developed on an inelastic strain basis for isothermal fatigue in the high-strain regime where the inelastic strainrange could be determined accurately. However, most power-generating equipment operates in the regime where the inelastic strains are small and difficult to determine with any degree of accuracy. This shortcoming led to the development of the total strain version of SRP (TS-SRP). Power-generating equipment seldom operates under isothermal conditions, and isothermal life prediction methods cannot be depended on to predict the lives of anisothermal cycles. To overcome this shortcoming, a method was proposed for extending TS-SRP to characterize anisothermal fatigue behavior and to predict the lives of thermomechanical fatigue (TMF) cycles using appropriate anisothermal data. The viability of this method, referred to as TMF/TS-SRP, was demonstrated using TMF data for two high-temperature aerospace alloys. In this report, data from the literature are used to examine the ability of TMF/TS-SRP to characterize the failure and flow behavior of three low-strength, high-ductility alloys widely used for ground-based power-generating equipment. The three alloys are type 304 stainless steel, 1Cr-1Mo-0.25V steel, and 2.25Cr-1Mo steel. Because of the limited nature of the data, it was possible to evaluate the characterization, but not the predictive capability of TMF/TS-SRP.

14. SUBJECT TERMS

Fatigue (metal); Life prediction; Strainrange partitioning; Constitutive modeling; Creep; Plasticity; Strain fatigue

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